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# The spatial and seasonal distributions of air-transport origins to the Antarctic based on 5-day backward trajectory analysis

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**Abstract**

Transport of moisture-bearing air to the Antarctic is one of the important factors that control the mass balance of the ice sheet. Here, we investigate the distribution of air-parcel transport using a backward trajectory analysis over the entire Antarctic ice sheet, based on whether the air parcel was located inside or outside of Antarctica at 5 days before arrival. At this time, we considered the air from outside Antarctica to be moisture rich. Oceanic air was found to dominate in West Antarctica throughout the year, whereas air from inland was more prominently distributed around East Antarctica, especially in summer. In East Antarctica, there was a significant seasonal variation: air from inland dominated in summer, while air of oceanic origin dominated in winter. The distribution of air parcels that came from oceanic/inland sources was similar to the accumulation map (based on satellite data), which indicates that oceanic air parcels could be a substitute for moisture transport to the Antarctic. To determine the future impacts of climate change (e.g., sea level rise), more precise predictions of the variations in the surface mass balance will be required. Our results contribute towards the improved understanding of the spatial distributions of accumulation and aerosols found in Antarctic snow and ice cores.


*Keywords:* Trajectory; Antarctic; Moisture transport; Surface mass balance

## 1. Introduction

Air transport to the Antarctic is an important factor controlling the Antarctic climate because it brings energy, moisture, and aerosols from regions outside of the ice sheet. There has been growing concern regarding the mass balance of the ice sheet under current and future global warming scenarios (Lightenberg et al., 2013; Rignot et al., 2011). Ice core data show similar temporal variations, but different ion concentration fluxes among drilling sites (Fischer et al., 2007). From these core data, it has been suggested that moisture sources have shifted under the influence of past climate changes (Masson-Delmotte et al., 2008, 2010; Stenni et al., 2004). However, the moisture sources determined by global climate models (GCMs) are subject to uncertainties, both in the past

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and the present, due to a lack of observational data over Antarctica and the surrounding ocean. If we are to develop improved estimates of the source and scale of these moisture sources, it will be necessary to undertake physical measurements, in addition to numerical simulations, to determine atmospheric transport mechanisms.

Moisture transport to the Antarctic has been investigated previously using backward trajectory analysis based on meteorological reanalysis data (Helsen et al., 2004; Reijmer et al., 2002; Schlosser et al., 2004; Suzuki et al., 2004, 2008). Using 5-day backward trajectory analysis, these studies concluded that the origin of moisture on the continent is the surrounding ocean. In contrast, Sodemann and Stohl (2009) simulated forward trajectories from the middle and lower latitudes over a period of about 10 days, and indicated a similar origin to that derived from the GCMs. Nevertheless, a gap remains in our approach to the analysis of moisture transport using trajectory analysis. Moreover, almost all studies of moisture transport based on 5-day backward trajectory analysis only simulated either drilling sites or coastal locations. To estimate the accumulation rate for the entire Antarctic ice sheet, moisture transport to the whole of the ice sheet must be considered, but there is only one forward projection modeling study tackling this problem at present, and no studies using backward projection.

The ion concentrations of surface snow sampled by the Japanese Antarctic Research Expedition (JARE) show spatial variations between coastal and interior regions (Motoyama, 2010; Suzuki et al., 2001). The $Na^+$ concentration is higher near the coast and lower in the interior, whereas the $Na^+$ concentration is higher in the interior. This suggests that air transport differs for the interior and coastal regions. However, few studies have examined actual air transport. JARE has conducted continuous atmospheric observations for more than 10 years, particularly of atmospheric aerosols, at Syowa Station near the coast of Antarctica. Atmospheric observations were also carried out over the winter of 1997 at Dome Fuji station in the interior of the continent (Yamanouchi et al., 1999). The $Na^+$ concentration in the air at Dome Fuji station undergoes a significant increase in winter (Hara et al., 2004). The above results confirm that air transport to the coastal and interior regions differs, and that seasonal variations exist in this transport pathway.

To interpret these observational data, Suzuki (2010) investigated the air transport routes to the Syowa and Dome Fuji stations and their monthly variations. At Syowa station, the air parcels in the mid-troposphere tended to come from the Atlantic Ocean, whereas those in the lower troposphere originated mainly from above the ice sheet. On the other hand, at Dome Fuji station, there was a clear seasonal variation in that most air parcels came from the ocean in winter, but tended to remain over the ice sheet for more than 5 days during the summer. So far, this kind of study, which compares coastal and inland sites, has only been conducted over limited areas; e.g., Dronning Maud Land (Suzuki, 2010) and the Ross Ice Shelf (Sinclair et al., 2010). Consequently, it is important to extend studies of this type to the whole of Antarctica if we are to better interpret the ice core, snow, and atmospheric data from different regions of the continent.

The International Trans-Antarctic Scientific Expedition (ITASE) was established to collect and interpret a continental-wide array of environmental parameters assembled through the coordinated efforts of scientists from several nations. Bertler et al. (2005) determined the spatial distribution of major ions and methyl sulfonate concentrations of surface snow over Antarctica based on a compilation of measured data. The distributions of $Na^+$ and $NO_3{}^-$ ions indicated that oceanic air influenced the coastal regions, whereas in the interior, a different atmospheric transport route was active, with snowfall bringing more $NO_3{}^-$ and less $Na^+$. Masson-Delmotte et al. (2008) focused on the δD and $\delta^{18}O$ isotope distributions, and found clear spatial distributions of δD and $\delta^{18}O$ linked to the changing Antarctic topography, as was also seen in the major ions and outlined above.

In the present study, we compare the observed distributions of surface snow data with calculations based on air transport to the Antarctic from two sources: one inside and one outside of Antarctica. The spatial distribution and seasonal variations of these sources are also considered. Air from outside the ice sheet transports moisture and minor atmospheric constituents; e.g., aerosols. Although this classification scheme is simple, it is hoped that such a comparison will help to clarify moisture and aerosol transport mechanisms to, and above, the Antarctic, and allow past climate changes to be identified based on interpretation of ice core data.

## 2. Data and methods

Trajectory analysis offers a useful approach to the identification of atmospheric air transport routes. In particular, the backward trajectory method can be used to determine the origin of air parcels responsible for the observed snow and atmospheric minor constituents (see Fig. 1 for examples). The Antarctica ice sheet covers a very large area, and has a wide range of altitudes. For example, the surface is more than 3500 m above sea level in the interior of the continent, whereas it is only a few meters above sea level in coastal regions. Consequently, selecting starting points for air parcels to be used in the calculations based on equal air pressure is not a suitable method, because each point would be at a different height above the ground. Instead, the starting points are set to be 1300 m above ground level over Antarctica. The vertical profiles of wind speed observed at Syowa station exhibit maxima, one of which is located at about 900 hPa in the lower troposphere. A height of 1300 m above the ground (about 850 hPa) corresponds to the free atmosphere, which reduces calculation errors associated with turbulence at the atmospheric boundary layer (ABL). To verify this starting altitude, we compared the results of trajectory analysis starting at 1300 m with that starting at 2000 m. While the two transport routes showed some small differences, they were essentially the same, so we assumed that calculations starting at 1300 m expressed atmospheric behavior at lower altitudes in the free troposphere. We used the National Institute of Polar Research (NIPR) trajectory model (NITRAM; Tomikawa and Sato, 2005) and ERA-Interim reanalysis data (Dee et al., 2011) to calculate air transport routes and their points of origin over a 1° × 1° grid covering Antarctica. The 3D (i.e., kinematic) trajectory analysis calculations were carried out with a time step of 1 h using the 6-hourly wind data from the ERA-Interim data, and starting every day at 1200 UTC for the period 1990–2009. The ERA-Interim dataset is on

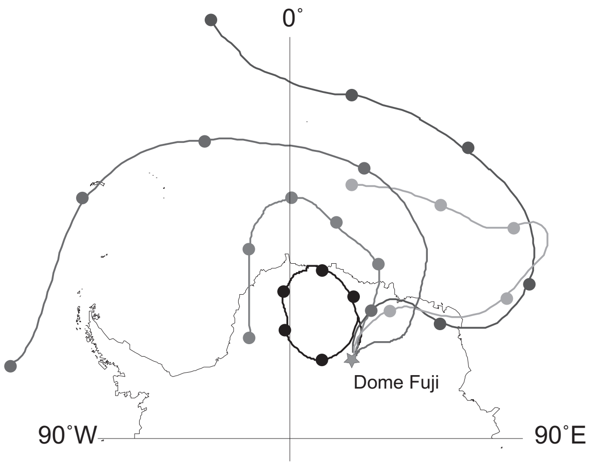


Fig. 1. Examples of backward trajectory analysis over Antarctica. The dots indicate the location of the air parcel at 1200 UTC each day for 5 days, and the lines are the trajectories.

a 1.5° × 1.5° grid format, with 37 levels and an interval of 6 h.

The 3D trajectories calculated in the troposphere may contain uncertainties due to factors such as errors in the wind data, in particular the vertical wind, and the limited data resolution. After 5 days, an accumulated horizontal error of up to 1000 km may occur due to the limited spatial resolution and the interpolation schemes used for the wind field (Kahl and Samson, 1986; Stohl et al., 1995). For this reason, the position of an air parcel 5 days before is taken as its point of origin, following the method used in earlier studies (Reijmer and Van den Broeke, 2001; Schlosser et al., 2004; Suzuki et al., 2004, 2008). We have evaluated the validity of this approach based on different assumptions about the origin of the air parcels. As air parcels are well mixed with the surrounding air in the ABL, the position at which an air parcel enters the free troposphere from the ABL can be regarded as its point of origin. Here, we computed the positions at which air parcels cross heights of 500 and 1000 m above ground level, and compared them with the locations of the air parcels 5 days before. The results indicated that the distribution of air parcels 5 days before was almost identical to the distribution of the positions where the air parcels cross the 500- and 1000-m levels. Therefore, in the present study, we define the location of an air parcel 5 days before as its point of origin.

Suzuki et al. (2008) pointed out that the air transport routes in the lower troposphere were very different under snowy and clear weather conditions. In snowy conditions, the air parcels came directly from the Atlantic Ocean, whereas they traveled along the coast in clear weather because the coastal regions are influenced by eastward winds from the semi-stationary waves. This means that the atmospheric transport of moisture to the Antarctic would be derived from air outside of Antarctica. In this study, we consider the boundary between regions of Antarctica in which air transport originates from inside or outside the continent. This boundary is defined based on whether the number of air parcels originating from inside the continent exceeds that from the ocean. By defining such a boundary, it is hoped that the principal transport pattern can be easily visualized at any given time, and that seasonal and annual variations induced by atmospheric circulation can be clarified. This would provide an effective method of analyzing ice core data from different drilling sites and so facilitate reconstruction of the paleoclimate and estimates of the accumulation rate over the whole ice sheet. We assigned the origin of each air parcel using the same method as Suzuki et al.

(2008), and based on the map of ocean and land areas shown in Fig. 2. The boundary between these areas is based on supposition; the land area includes three large ice shelves, while the Antarctic Peninsula is in the ocean area. The average air-parcel origins were determined from annual and seasonal distributions for the period 1990–2009. We first produced monthly averaged distributions of air-parcel origins and found significant seasonal variations. In this study, we assume that the summer season is from December to February, and the winter season from March to November, based on the seasonal distribution of air-parcel origins. During the winter season, there are slight differences in the distributions from month to month. It is important for interpretation of the annual averaged boundary to consider the influences of air transport from outside of Antarctica during the long winter.

## 3. Results and discussion

Fig. 3 indicates the average annual and seasonal distributions of air-parcel origins for 20 years. In West Antarctica, air parcels with an oceanic origin dominate throughout the year, suggesting that the sea surface temperature and oceanic heat transport have a significant influence on the climate in this region. Our results indicate that the recent increase in *P-E* in West Antarctica (Bromwich et al., 2011) is likely to be due to air transport from outside Antarctica. On the other hand, in East Antarctica, the distribution of air-parcel origins changes more gradually from the inland to the coast. In the interior region, an inland origin is dominant, whereas this situation is reversed at the coast. The dominant origin changes at around 73–75°S, where altitudes are in the range 1500–2000 m above sea level in East Antarctica. The distributions shown in Fig. 2 form an enclosure that connects the Ross, Ronne-Filchner, and Amery ice shelves. This is especially clear in summer, although even for the winter and annual means, the specific distributions of air parcels of oceanic origin are similar to those in the summer. The ocean-dominated regions are distributed outside of the enclosure, and face areas with a high density of cyclone systems over the ocean (Jones and Simmonds, 1993). The line from Ronne-Filchner to Ross follows the terrain, whereas, in contrast, the lines from Amery to Ronne-Filchner, and from Ross to Amery, cut straight across the topography on the east side of the ice shelves. Cyclonic activity around the ice sheet can frequently drive air masses into the interior, and these air masses might be capable of scaling steep slopes and entering the interior around the east side of the ice shelves.

The shape of the region around the South Pole with a high occurrence of air parcels of inland origin is similar to that of the low accumulation area seen on satellite maps (Arthern et al., 2006), which indicates that they may be related in some way. As the moisture content of air decreases with temperature, air that has traveled over the ice sheet for a long time contains less

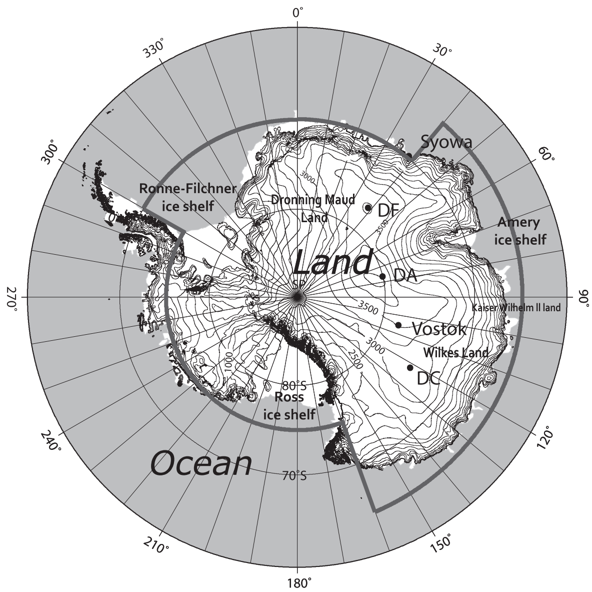


Fig. 2. Topographic map of Antarctica showing drilling sites and Syowa Station. DA: Dome A, DF: Dome Fuji, DC: Dome C. The boundary between ocean- and land-dominated air parcels is shown as a gray line.

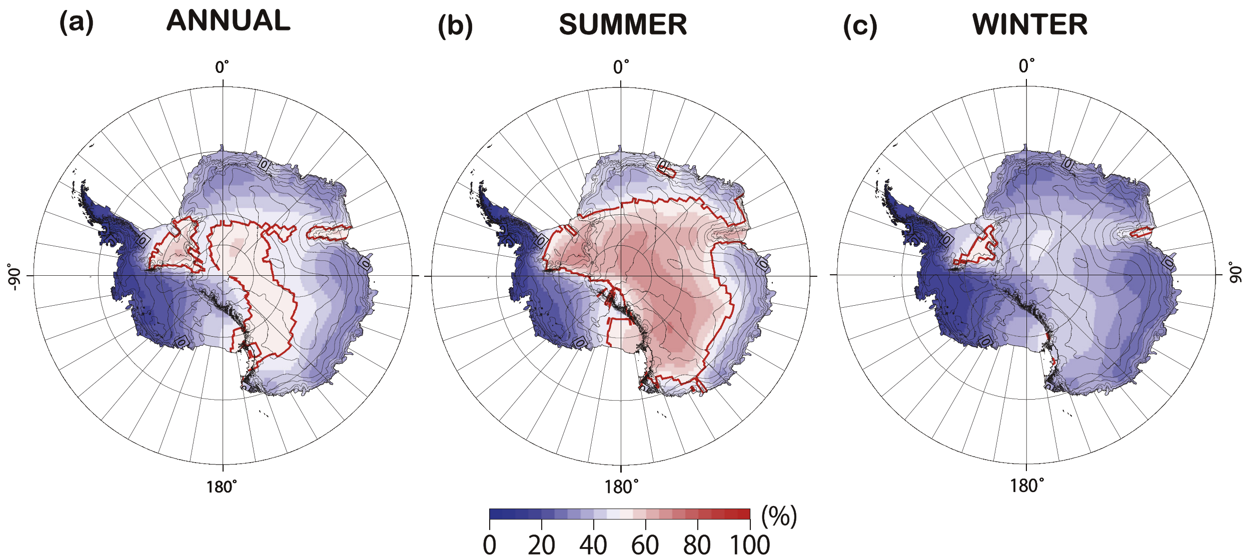


Fig. 3. (a) Annually averaged distributions of air-parcel origins over Antarctica; i.e., ice sheet or ocean. The color scale corresponds to the fraction of air parcels with continental origins for each 1° × 1° grid square, with 100% representing a fully continental origin. The bold red line indicates the region in which half of the air parcels were derived from outside of the ice sheet. (b) As (a), but averaged over the summer season. (c) As (a), but averaged over the winter season. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

moisture, leading to low accumulation in this region. From satellite maps, we can identify a snow megadune area whose appearance suggests that its formation may have been influenced by air parcels with an inland origin (Fahnestock et al., 2000). We suggest that this area was produced by recrystallization of snow under low precipitation conditions, and such structures may therefore be evidence of air parcels with inland origins. This is a subject for future work, and will require the use of advanced processing techniques to aid interpretation of the satellite data.

Fig. 4 shows the distributions of the 5-days-prior air parcel altitudes in the form of annual and seasonal means. The vertical scale is the true altitude above sea level, and not the height above the terrain. The annual and summer distribution patterns are similar, with the air-parcel origin points following the topography. Most show a dependence on the starting point altitudes; for example, in the interior region where altitudes are above 3000 m, the air-parcel origin heights are above 4300 m, whereas in the coastal regions they are about 2000 m. In short, typical air transport pathways to the Antarctic involve very little vertical movement of air. However, in winter, there is a significant change around Wilkes Land, including the Vostok and Dome C stations in East Antarctica. In most of these areas, air parcels with a low-altitude origin dominate in winter, whereas there is no noticeable vertical change around Dronning Maud Land, including the Dome Fuji and Dome A stations. Seasonal differences in air-parcel origin altitude around East Antarctica have not been discussed in earlier studies, but there is clearly a seasonal variation in the area between the Amery and Ross ice shelves in East Antarctica.

The average amount of precipitable water (PW) over Antarctica has been predicted using satellite data, and the PW at Dome C was observed to be larger than that at Dome A and Dome Fuji in terms of both annual and wintertime means (Saunders et al., 2009). Their results indicated that the wintertime PW contribution to the annual PW at Dome C was about 10% higher than at Dome A and Dome Fuji. Around Dome C and Vostok in Wilkes Land, the influence of air transported from outside Antarctica seems to be stronger than in other areas, especially in winter, as can be seen in Fig. 3(c). Tomasi et al. (2011) determined the PW value using rawinsonde measurements at Dome C, and found it to be about 0.4 mm in winter. In comparison, the satellite results were still in fairly good agreement with the rawinsonde results. Snowfall and accumulation may show seasonal variations, and there is a possibility that the isotope concentrations in ice cores obtained at Dome C have been influenced by snowfall containing external information in winter. In contrast, the influence of seasonal variations on air and moisture transport is minimal around the high interior region of Dronning Maud Land, including Dome Fuji and Dome A. However, as no long-term study of snowfall and its components has been

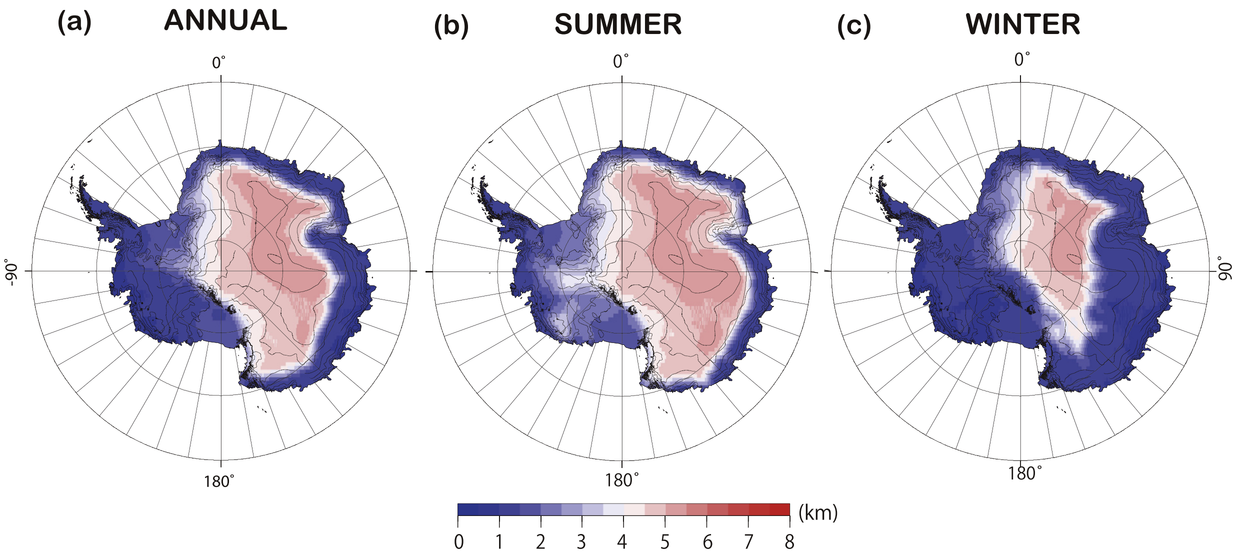


Fig. 4. (a) Annually averaged distributions of altitudes of air-parcel origins. The altitudes represent heights above sea level and the starting points of the air parcels are 1300 m from the surface, which varies with the topography. (b) As (a), but averaged over the summer season. (c) As (a), but averaged over the winter season.

carried out around Wilkes Land, this relationship should be confirmed in a future study.

The boundary between regions influenced mainly by air parcels with terrestrial or oceanic origins was determined using a 5-day backward trajectory analysis, and the physical validity of this approach from a meteorological viewpoint will now be discussed. Fig. 5 shows the residence times of air parcels over the ice sheet in terms of annual and seasonal averages. As the calculation period is 5 days, the maximum residence time is 120 h. The spatial distribution of the residence times is similar to that of the origin of air parcels (Fig. 3), both for the annual and seasonal cases. Air parcels with an inland origin travel over Antarctica for a relatively long period, whereas those with an oceanic origin only have a short period of contact with the ice sheet, and are mainly influenced by the sea. The use of a 5-day trajectory analysis is appropriate for studying air transport of short-lived aerosols to the Antarctic because most air parcels have residence times over Antarctica of less than 5 days. Comparing the air-parcel origin distribution with the observed ion concentrations in the surface snow, the boundary seems to be consistent with the distribution of $Na^+$ and $Cl^-$ concentrations (Bertler et al., 2005). There are some areas of disagreement in Wilkes Land, especially around Kaiser Wilhelm II Land, whereas there is good agreement between the observed ion concentrations and the calculated boundary around Dronning Maud Land and West Antarctica. Although the measured $Na^+$ concentration in Wilkes Land was low in winter, Fig. 4(c) suggests that the air parcels are mainly of oceanic origin. The reason for such disagreement may be that, because of the high altitude, precipitation in this area is light, so that the ion concentration reflects only summertime variations (Dahe et al., 1999).

The ion concentrations in surface snow (Suzuki et al., 2001) from the coastline to about 200 km inland have high concentrations of $Na^+$ and $Cl^-$, whereas they are low in regions more than 200 km from the coast. On the other hand, the concentration of $NO_3{}^-$ is low in the coastal region and increases at about 600 km from the coast. It is assumed that air parcels containing $NO_3{}^-$ are transported by the global atmospheric circulation in the stratosphere. Above the ice sheet, these air parcels cool and condense, finally dropping to the surface through the stratosphere and troposphere (Iwasaka, 1986; Kamiyama et al., 1996). The $NO_3{}^-$ concentration increased in the interior region (Bertler et al., 2005; Suzuki et al., 2001), which is consistent with a region receiving air parcels from an inland origin. As the region between 200 and 600 km from the coastline is under katabatic wind control, the concentrations of several ions are less in this region than in other areas (Furukawa et al., 1996). The boundary between the inland and ocean dominated air parcels is located in this zone of katabatic winds at altitudes between 1000 and 2000 m. Cyclonic disturbances cannot usually penetrate the interior due to the steep slope between the coast and interior regions. Particularly in summer, wind speeds

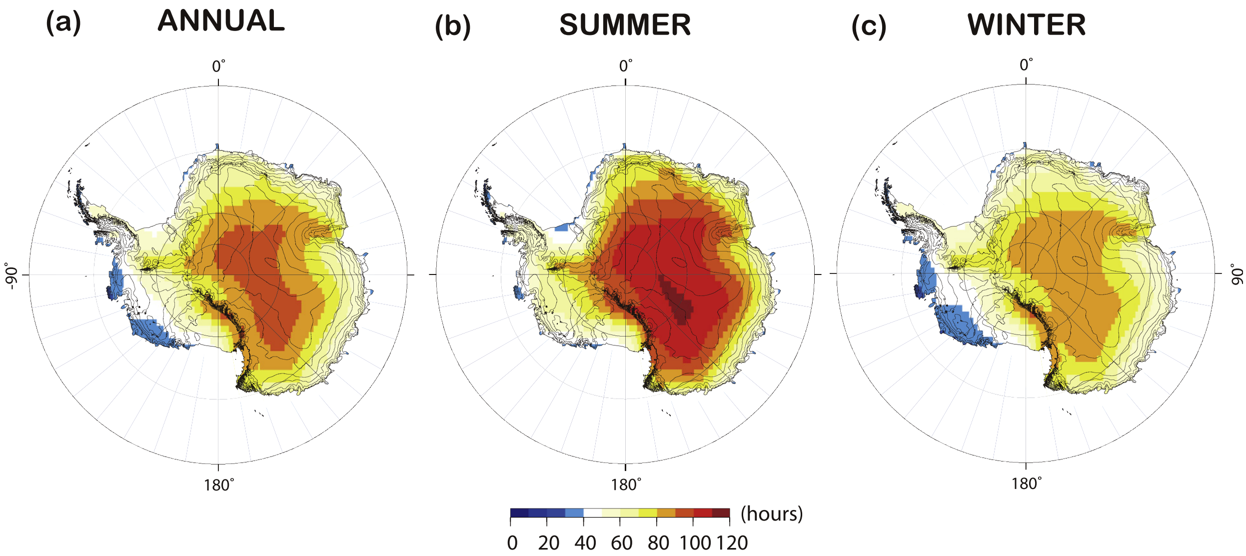


Fig. 5. (a) Annually averaged distributions of air-parcel residence times over the ice sheet during a 5-day period (120 h). (b) As (a), but averaged over the summer season. (c) As (a), but averaged over the winter season.

decrease, making it even more difficult for air parcels to move inland. In winter, air parcels tend to enter the interior with the development of the westerlies. Masson-Delmotte et al. (2008) suggested that significant changes in deuterium excess values occur below and above an elevation of 2000 m, indicating that dynamic atmospheric moisture advection processes may induce differences in moisture origins and atmospheric transport pathways. Our results are consistent with this interpretation of the observed water isotopes in the surface snow, and indicate different air-parcel origins for coastal and interior regions.

We suggest that the air-parcel origin distribution proposed in the present paper coincides with the region influenced by cyclonic disturbances (which are subject to seasonal variation and temporal interaction with the ocean), as well as the region influenced by the terrain of Antarctica. The characteristics of accumulation in Antarctica have been studied previously using satellite microwave data (Arthern et al., 2006; Yamanouchi and Wada, 1992; Zwally, 1977) and water isotope data from surface snow (Masson-Delmotte et al., 2008). However, in the present study, using the calculated air-parcel origins, we have been able to extend estimates of the effect of oceanic influences, including moisture transport, over the entire ice sheet of Antarctica.

## 4. Conclusions

We have investigated the distribution of air-parcel origins over Antarctica, based on whether they originated from the ice sheet or from outside the continent. Backward trajectory analyses were calculated that would drive the moisture transport in the lower troposphere. Although the distribution exhibited similar features throughout the year, there were also seasonal variations. The distribution enclosed an area that connected the Ronne-Filchner, Amery, and Ross ice shelves, and the degree of oceanic influence showed seasonal variations. In summer, most of the air parcels originated over the ice sheet, having traveled a long distance over the continent. In contrast, in winter, oceanic air parcels penetrated to all parts of Antarctica. In addition, we compared the calculated air-parcel origin distributions with surface snow measurement data. The $Na^+$ concentration seemed to decrease from the coastal region inwards, corresponding to the weakening influence of air parcels with oceanic origins. Overall, the distribution of air-parcel origins over Antarctica is consistent with the observed ion concentrations in surface snow. We suggest that the enclosed nature of the distribution should be verified by acquiring more measurement data, in addition to carrying out higher resolution modeling in the future. However, the present study has proposed the first map of air-parcel origins for the whole Antarctic.

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